WeedTurf: a predictive model to aid control of annual summer weeds in turf

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Predicting weed emergence is useful for planning weed management programs. Unfortunately, our ability to anticipate initial emergence and subsequent levels of emergence from simple field observations or weather reports is often inadequate to achieve optimal control. Weed emergence models may provide predictive tools that help managers anticipate best management options and times and, thereby, improve weed control. In this study, the germination characteristics of four annual grass weeds (large crabgrass, goosegrass, green foxtail, and yellow foxtail) were investigated under different temperatures and water stresses to calculate base temperatures and base water potentials. These parameters were used to develop a mathematical model describing seedling emergence processes in terms of hydrothermal time. Hydrothermal time describes seed germination in a single equation by considering the interaction of soil water potential and soil temperature. The model, called WeedTurf, predicted emergence with some accuracy, especially for large crabgrass (lowest efficiency index [EF] value 0.95) and green foxtail (lowest EF value 0.91). These results suggest the possibility of developing interactive computer software to determine the critical timing of weed removal and provide improved recommendations for herbicide application timing.

Nomenclature: Goosegrass, *Eleusine indica* (L.) Gaertn. ELEIN; green foxtail, *Setaria viridis* (L.) Beauv. SETVI; large crabgrass, *Digitaria sanguinalis* (L.) Scop. DIGSA; yellow foxtail, *Setaria glauca* (L.) Beauv. SETLU.

Key words: Annual grass weeds, emergence prediction, hydrothermal time, turf.

Weeds are a major problem in turf and are often the result of improper site preparation or inappropriate management. Because weeds become established more readily in thin and weak turf areas, the best defense against weeds is a vigorous and healthy turf (Gaussoin and Martin 1994). In addition to good weed control, one of the most important objectives in turf management on golf courses is wise herbicide use, which can be facilitated by predicting the time and extent of weed emergence (Oriade and Forcella 1999). If we are able to forecast when weeds emerge and the length of the emergence period, we can optimize herbicide application timing and rate. In particular, the prediction of weed emergence can contribute to the timing of preemergence herbicide applications to control annual summer grass weeds. These chemicals are applied when the turf is growing and well established but before weed emergence (Bingham et al. 1995). Improper timing is a major cause of poor weed control by these herbicides because they lose effectiveness if applied too early or after the weeds have emerged (Yelverton 1996). The prediction of weed emergence also can help to detect very early and very late emerging plants that may contribute to competition and seed return (Grundy 2002). Therefore, development of accurate models to describe weed emergence dynamics is useful for planning a weed management program.

The first important step to create predictive models is to understand the factors that control the pattern of seedling emergence. The timing of weed emergence in turf will vary according to the interaction of environmental conditions, turf management, and weed species. The most important environmental factor governing weed emergence is the combination of soil temperature and soil water potential. Description of seed germination is possible in a single equation by considering only these two factors as "hydrothermal time." Hydrothermal time defines the interaction of water potential above a threshold level, temperature above a threshold level, plus time in a single function (Bradford 1995; Gummerson 1986). There are many examples where this concept has been used with success in simple models of emergence (Alvarado and Bradford 2002; Chang and Bradford 1999; Dehal and Bradford 1994; Grundy et al. 2000; Rowse and Finch-Savage 2003). For good emergence prediction, monitoring daily microclimatic conditions near the surface is necessary (Grundy 2002) but requires intensive effort and is not always possible. Soil physical models may be valuable tools for simulating daily soil temperature and soil water content near the surface. Unfortunately, near-surface microclimatic conditions are difficult to simulate correctly because of rapid changes in response to atmospheric conditions. Flerchinger and Saxton (1989a, 1989b) developed the Simultaneous Heat and Water (SHAW) model to simulate heat and water movement through plant cover, residues, and soil. Pierson et al. (1992) compared SHAW results with those from two less complex models and found that it provided the most accurate simulation of near-surface soil temperatures. SHAW model output also was evaluated by Flerchinger and Hardegree (2004), who suggested that the model can be used to simulate soil temperature and water conditions to predict potential seed germination response for postfire revegetation in rangelands.

The objectives of this study were (1) to determine base temperature and base water potential, (2) to evaluate the

TABLE 1. Constant temperatures used to calculate the base temperature.

Species	Temperatures
	C
Large crabgrass	4, 7, 10, 13, 16, 20, 24, 28
Green foxtail	6, 9, 12, 15, 18, 21, 24, 28
Goosegrass	4, 8, 12, 16, 20, 25, 28
Yellow foxtail	4, 7, 10, 13, 16, 20, 24, 28

SHAW model for its ability to predict daily soil temperature and soil water content near the surface, and (3) to construct and evaluate a model to describe the emergence of four annual grass weeds: large crabgrass, goosegrass, green foxtail, and yellow foxtail.

Materials and Methods

The first step in constructing the predictive model was to calculate base temperature and base water potential for the four species. These are the threshold levels beneath which germination does not occur. After evaluation of the ability of the SHAW model to predict daily soil temperature and soil water content in the seed germination zone, base temperature, and base water potential were incorporated into an appropriate hydrothermal time model based on daily site-specific values of soil temperature and water potential.

Base Temperature

Base temperatures were calculated with the method proposed by Roché et al. (1997). Four replicates of 100 seeds of each of the four species were incubated at a range of constant temperatures (Table 1) in 10-cm-diam transparent plastic containers with 50 ml of water. All seeds were sterilized with sodium hypochlorite solution and rinsed with deionized water before testing. Germination was recorded at about 12-h intervals until no further germination occurred for 4 d. The seeds were defined as germinated at the time of visible radicle emergence.

The germination time course was analyzed using a logistic function in the Bioassay97 program (Onofri 2001) and the time necessary for 50% germination was estimated. A linear regression, estimated using the bootstrap method (Efron 1979), provided the best fit of germination rate (reciprocal of time to 50% germination) against incubation temperature. The base temperature was estimated as the intercept of the regression line with the temperature axis.

Base Water Potential

Base water potentials were calculated according to Roman et al. (1999). Polyethylene glycol (PEG 6000)[1] was used to create solutions with water potentials of 0, −0.03, −0.06, −0.2, −0.5, −1.1, −1.5, and −2.1 MPa, prepared according to Wood et al. (1993). Four replicates of 100 seeds each were placed in 10-cm-diam transparent plastic containers lined with absorbent filter paper to which were added 50 ml of water or one of the seven PEG solutions. The containers were fitted with tight lids to prevent evaporation and PEG-solution osmotic concentration was controlled daily using a Freezing Point Osmometer.[2] The containers were

placed in a seed germinator at a constant temperature of 25 C and photoperiod of 14:10 h (light–dark). Germinated seeds were counted and removed at about 12-h intervals, and the experiment was stopped after 4 d without germination. Germination was recorded at the time of visible radicle emergence. Seeds that failed to germinate were washed in deionized water to eliminate PEG residues and transferred into dishes with water and optimal conditions for germination (constant temperature of 25 C for large crabgrass and yellow foxtail and 35/21 C [day/night] for goosegrass). This was done to verify the number of viable nondormant seeds per treatment. Green foxtail seeds, harvested in 2002 for this experiment, did not germinate because of dormancy and determination of the base water potential of this species was not possible.

The germination time course was modeled using a logistic function in the Bioassay97 program (Onofri 2001) from which the time of 50% germination was estimated. Base water potential was calculated by regressing time to 50% germination against water potential using the bootstrap method (Efron 1979). The base water potential was estimated as the intercept of the regression line with the water potential axis. The base water potential of green foxtail was found using an iterative process that consisted of changing the base water potential in a hydrothermal time equation until the simulation conformed satisfactorily with the observed emergence data (Ekeleme et al. 2004). The best fit appeared to occur when base water potential was −0.70 MPa. After calculation of base temperature and base water potential, seed germination time was analyzed using the hydrothermal time concept.

Soil Temperature and Soil Water Potential

The SHAW model was tested using data collected at the experimental farm of Padova University in Legnaro (northeastern Italy, 45°12′N, 11°58′E, 6 m above sea level) on two different soils: a native loam soil (fulvi-calcaric Cambisoil with a loamy texture in the upper 80 cm 41% sand, 46% silt, 13% clay; organic carbon 1.2%, pH 7.07) and a sandy-loam soil (80% river sand [0.2 to 2 mm diameter] and 20% native loam soil). Temperature was monitored beginning on February 15, 2001, in the sandy-loam soil using three thermocouples buried 2.5 cm deep and connected to a data logger.[3] The data logger took readings of temperature every 30 s, then compressed into an average every 30 min. Three other thermocouples were buried under the native loam soil in 2003. Time domain reflectometry (TDR)[4] was used to measure moisture content in both soils once a day beginning on February 15, 2002 (in the days with precipitation or irrigation above 20 mm, soil moisture content was not measured and the value corresponding to the saturated soil moisture content was recorded). Two 30-cm-long steel TDR probes were placed horizontally at a depth of 5 cm. Soil water content was converted to water potential using the soil water retention curve derived in the laboratory with soil samples for both soil types (Bussoni and Mecella 1997).

Daily weather data (air temperature, wind speed, humidity, precipitation, and solar radiation) are required input for the SHAW model and were recorded at a weather station located approximately 100 m from the site.

SHAW model simulation of soil water content and soil temperature estimated under bare soil was compared with

TABLE 2. Data sets of weed emergence used for fitting and for evaluating the model. When the set of emergence was used to calibrate the model, it was specified whether measured or simulated soil parameters were used.

	Years		
Soil type	2001	2002	2003
Sandy-loam	Calibration data set	Calibration data set	Calibration data set
	Measured soil temperature	Measured soil temperature	Measured soil temperature
	Simulated soil water content (SHAW)	Measured soil water content	Measured soil water content
Loam	Evaluation data set	Evaluation data set	Calibration data set
			Measured soil temperature
			Measured soil water content

measured field data in sandy-loam (2001–2002–2003 temperature and 2002–2003 water content) and native loam (2003 temperature and 2002–2003 water content) soils using the model efficiency index (EF) (Loague and Green 1991) and mean bias error (MBE) (Willmott 1982). The model EF is calculated as:

$$EF = \frac{\sum_{i=1}^{n} (O_i - \bar{O})^2 - \sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \qquad [1]$$
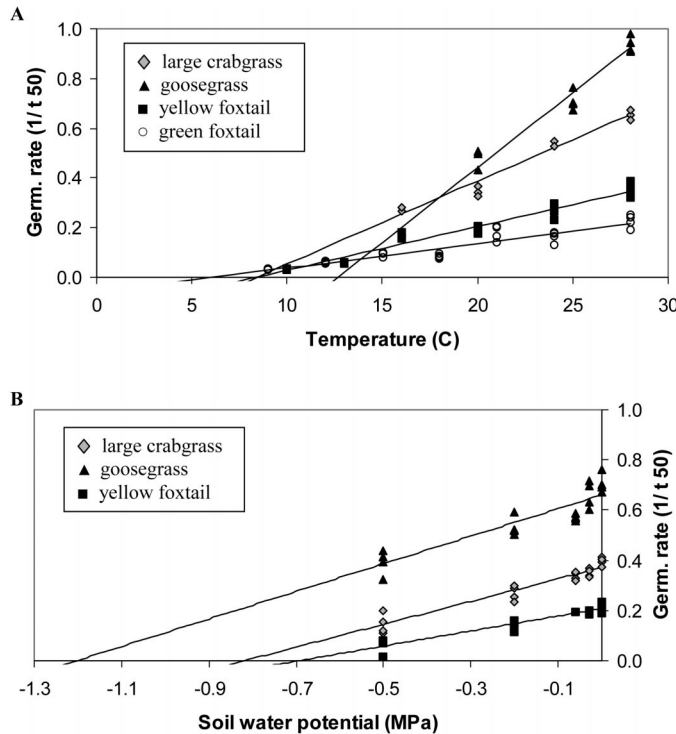

A

B

FIGURE 1. Linear relation between incubation temperature (A) and germination rates (1/t50) and between water potential and germination rates (B) for large crabgrass, goosegrass, yellow foxtail, and green foxtail. Base temperatures and base water potentials for germination were estimated as the intercept of the regression lines with the x axis. Estimated equations for regression lines to extrapolate base temperatures are: $y = -0.76 + 0.06 \times$ ($r^2 = 0.89$) for goosegrass; $y = -0.28 + 0.03 \times$ ($r^2 = 0.98$) for large crabgrass; $y = -0.15 + 0.02 \times$ ($r^2 = 0.97$) for yellow foxtail; $y = -0.06 + 0.01 \times$ ($r^2 = 0.96$) for green foxtail. Estimated equations for regression lines to extrapolate base water potential are: $y = 0.66 + 0.55 \times$ ($r^2 = 0.84$) for goosegrass; $y = 0.37 + 0.45 \times$ ($r^2 = 0.94$) for large crabgrass; $y = 0.21 + 0.30 \times$ ($r^2 = 0.94$) for yellow foxtail. Estimated base temperatures and water potentials are reported in Table 3.

where P_i is the simulated value, O_i the measured value, and $\bar{O}$ the mean of measured value. The value of EF can range from 1 downward. An EF value of 1 would mean that the model produced exact predictions. The MBE is related to magnitude of values under investigation and is an indication of the average deviation of the predicted from the measured values. It is calculated as:

$$MBE = \frac{1}{N} \sum_{i=1}^{N} (P_i - O_i) \qquad [2]$$

where N is the number of observations. A negative MBE occurs when the model underestimated the observed values (i.e., when predictions are smaller in value than observations).

Monitoring of Seedling Emergence

To evaluate model performance in predicting cumulative relative seedling emergence, the timing of seedling emergence of large crabgrass, goosegrass, green foxtail, and yellow foxtail was studied from 2001 to 2003 in the native loam soil and in the sandy-loam soil. Turf, comprised 75% ryegrass (*Lolium perenne* L. 'Barsportivo' and 'Brightstar') and 25% bluegrass (*Poa pratensis* L. 'Midnight' and 'Bartitia'), covered both soils. The turf was mowed every 7 to 10 d to 3 cm and fertilized and irrigated when necessary to prevent any signs of stress.

Mature seeds of the four weed species were harvested each year in October from natural populations growing on the farm. In November of each year, using a tubular soil sampler, 88 soil cores (1 cm in diameter and 2.5 cm deep) were taken in an area of 30 by 120 cm. The spatial arrangement of the cores was that of a lattice with five rows separated from one another by 7 cm, and cores were spaced at 7 cm within each row. Thus, the first, third, and fifth rows had 18 cores each; and the second and fourth rows each had 17 cores. In these areas, the grass had been eliminated with glufosinate to simulate turf that was weak or absent and that favored weed emergence. Then, using funnels, the weed seeds were sown into the small holes to achieve a density of 2,500 seeds m^{-2}. Emerged seedlings were counted and removed twice weekly throughout the emergence period.

Hydrothermal Time and Cumulative Seedling Emergence

The modeling approach was based on concepts developed by Forcella (1998). This model, called WeedCast (Archer et al. 2001), predicts the rate of weed emergence in arable soil.

TABLE 3. Parameters and input variables of the hydrothermal time model (WeedTurf) used to simulate weed emergence. Numbers in parentheses represent the standard errors of calculated base temperatures (T_b) and base water potentials (Ψ_b).

Species	T_b	Ψ_b	T_o	K_t	a	b
	C	MPa	C			
Large crabgrass	8.4 (1.07)	−0.83 (0.255)	26	0.50	10.1	0.008
Green foxtail	6.1 (1.51)	−0.70 (—)	26	0.30	6.9	0.006
Goosegrass	12.6 (0.64)	−1.21 (0.480)	26	0.60	6.2	0.008
Yellow foxtail	8.3 (0.75)	−0.69 (0.017)	25	0.13	4.3	0.008

The basic concept of the WeedCast model is that seeds of all species accumulate hydrothermal time according to the soil temperature only when the soil water potential is above a base value. Soil Growing Degree Days ($SGDD_i$) are a combination of soil temperature and soil water potential and are calculated as:

$$SGDD_i = n \times \max(Ts_i - T_b, 0) + SGDD_{i-1} \quad [3]$$

where $n = 0$ when $\Psi_{si} \leq \Psi_b$, $n = 1$ when $\Psi_{si} > \Psi_b$, Ts_i is the average daily soil temperature at 2.5-cm depth, T_b

and Ψ_b are the base temperature and water potential thresholds for each weed species, and Ψ_{si} is the average daily soil water potential at 5-cm depth. Models that predict weed germination in arable soils usually accumulate temperature from the date of soil cultivation. In turf, no sowing date is available from which to start accumulation of SGDD, so the first day of the year was used (January 1).

Cumulative relative seedling emergence (CRSE) is expressed by a Gompertz function, as follows:
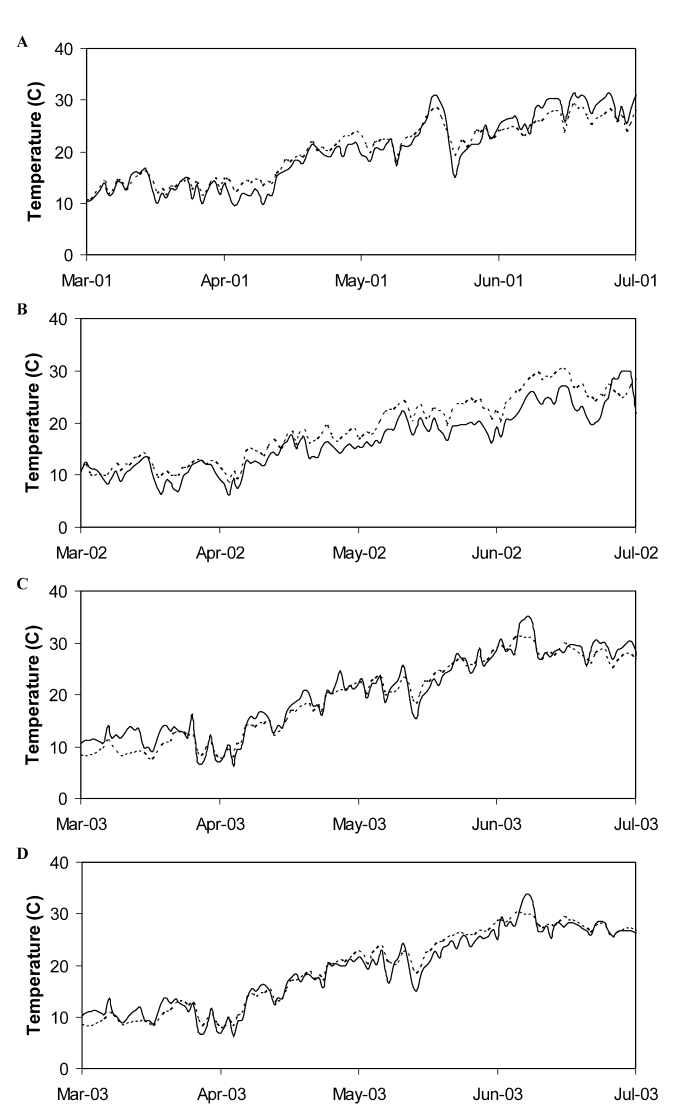

FIGURE 2. Simulated (solid line) vs. measured (dotted line) daily soil temperatures during the germination period at a depth of 2.5 cm under bare sandy-loam soil in 2001 (A), 2002 (B), and 2003 (C), and in 2003 under loam soil (D).
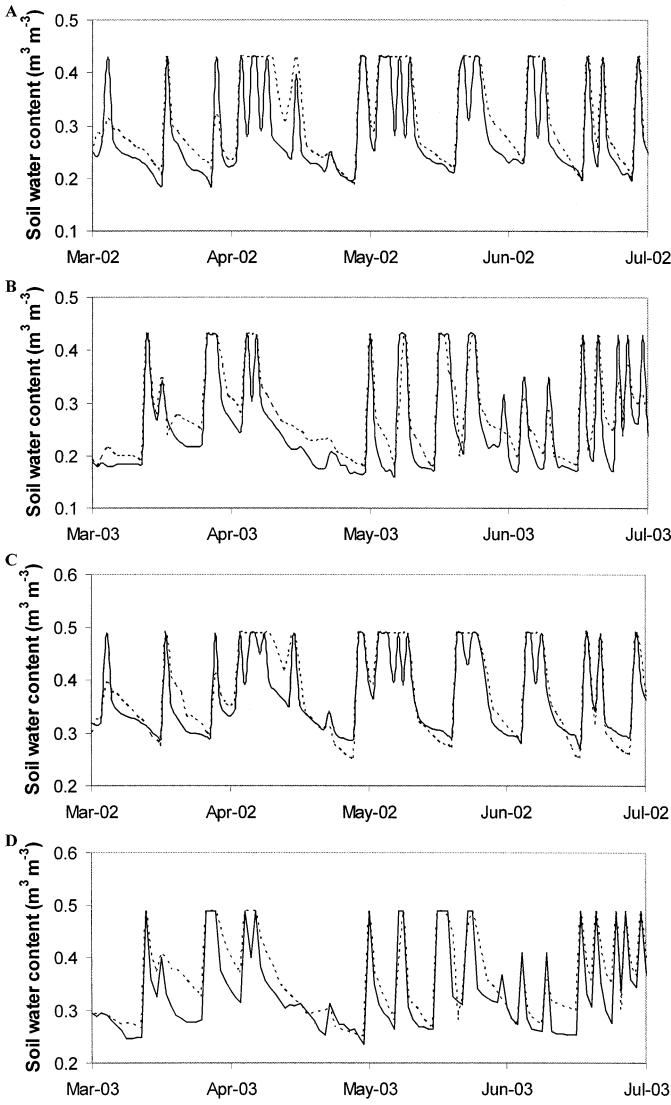

FIGURE 3. Simulated (solid line) versus measured (dotted line) daily soil water content during the germination period at a depth of 2.5 cm under bare sandy-loam soil in 2002 (A) and 2003 (B), and in under loam soil in 2002 (C) and 2003 (D).

TABLE 4. Model efficiency index (EF), mean bias error (MBE), and coefficient of the linear regression (m) between observed and simulated data. A comparison between the emergence simulations of WeedTurf obtained using measured soil temperature and water content and using the parameters estimated by the Simultaneous Heat and Water (SHAW) model (calibration data set).

Species	Soil type	Year	WeedTurf			WeedTurf + SHAW		
			EF	MBE	m	EF	MBE	m
				%			%	
Large crabgrass	Sandy-loam	2001	0.99	0.4	0.97	0.96	−4.4	1.00
	Sandy-loam	2002	0.96	5.0	0.96	0.98	−1.0	1.10
	Sandy-loam	2003	0.98	−1.8	0.98	0.99	−0.6	1.01
	Loam	2003	0.99	−0.2	0.96	0.96	3.9	0.88
Green foxtail	Sandy-loam	2001	0.96	−2.0	1.03	0.87	−5.4	1.06
	Sandy-loam	2002	0.93	7.6	1.01	0.97	−0.3	1.03
	Sandy-loam	2003	0.98	0.7	1.00	0.97	−1.8	1.07
	Loam	2003	0.98	−0.8	1.00	0.95	6.4	0.87
Goosegrass	Sandy-loam	2001	0.97	−3.1	0.97	0.88	−10.8	0.79
	Sandy-loam	2002	0.96	3.6	0.93	0.98	−4.0	1.00
	Sandy-loam	2003	0.97	−0.5	1.02	0.97	0.1	0.88
	Loam	2003	0.99	0.3	0.97	0.99	0.9	0.99
Yellow foxtail	Sandy-loam	2001	0.77	10.4	0.76	0.88	6.7	0.83
	Sandy-loam	2002	0.96	−2.4	0.91	0.80	−9.1	0.87
	Sandy-loam	2003	0.89	−5.5	0.97	0.92	−4.8	0.98
	Loam	2003	0.99	0.1	0.91	0.94	5.3	0.80

$$\text{CRSE} = 100 \exp(-a \exp(-b \, \text{SGDD})) \qquad [4]$$

where a represents a SGDD lag before emergence starts and b represents the rate of increase of emergence once it is initiated. The Gompertz equation is a standard and flexible function often used to describe the processes of germination and emergence (Forcella 1998).

Application of this model to our emergence data showed the model's inability to predict the germination rate during periods when temperatures were above an optimum level (data not shown). Therefore, modification of the hydrothermal time model was necessary so that it could describe the germination rate reduction and nongermination that occurred at supraoptimal temperatures. Bradford (2002) observed that the decrease in germination rates at supraoptimal temperature was because of an increase in the Ψ_b threshold for germination as temperature rose above the optimum (T_o). In other words, the Ψ_b values increased linearly (became more positive) until it reached 0 MPa at a temperature defined as the ceiling temperature (maximum threshold temperature at which germination is prevented). Consequently, Equation 1 was modified as suggested by Bradford (2002) so that, when $\text{Ts}_i < T_o$: $n = 0$ when $\Psi_{si} \leq \Psi_b$, $n = 1$ when $\Psi_{si} > \Psi_b$; and when $\text{Ts}_i > T_o$: $n = 0$ when $\Psi_i \leq \Psi_b + K_t (\text{Ts}_i - T_o)$, $n = 1$ when $\Psi_i > \Psi_b + K_t (\text{Ts}_i - T_o)$; T_o is the optimum temperature and K_t is the slope of the relationship between Ts_i and Ψ_b in the supraoptimal temperature range.

For modifying the equation, the values of T_o and K_t were systematically varied in an iterative fashion until the best simulations were obtained for each species. Initially, hydrothermal time was recalculated for different values of T_o and with $K_t = 0$, then K_t was varied incrementally to find the combination between the values of K_t and T_o giving the best simulation. The data used to estimate these parameters and a and b values of the Gompertz function were soil temperature, soil water content (converted to water potential), and the emergence sequences recorded from 2001 to 2003 in sandy-loam soil and 2003 in native loam soil (calibration data set) (Table 2). Given that no measured data of soil water content were available in 2001 in the sandy-loam soil, the SHAW model simulation was used to replace the missing data of soil water content for the estimation of a and b coefficients of the Gompertz function. The model based on these modified functions henceforth will be called "WeedTurf."

To evaluate model performance, simulated emergence from WeedTurf was compared with observed emergence data obtained in the native loam soil from 2001 to 2002 (evaluation data set) using the model EF (Loague and Green 1991), the MBE (Willmott 1982), and the coefficient of the linear regression (m) between observed and simulated data.

Results and Discussion

Base Temperature and Base Water Potential

Base-temperature estimates made by extrapolating the linear relationship between germination rate and incubation temperature were very similar for large crabgrass and yellow foxtail (Figure 1; Table 3). Green foxtail was able to germinate at a lower temperature than the other species. As expected, the late-spring emerging goosegrass required higher temperatures to begin accumulating the growing degree days needed for germination.

All species showed high sensitivity to water stress. In contrast to the WeedCast model that uses −5 MPa as base water potential (averaged over the top 5 cm of soil) for yellow foxtail, this species was very sensitive to water stress with a calculated base water potential of −0.69 MPa (Figure 1; Table 3). The moisture threshold level of large crabgrass was −0.83 MPa, whereas Forcella et al. (2000) estimated a base water potential of −0.5 MPa for this species. Goosegrass did not germinate if water potential was less than −1.21 MPa. Using seeds collected from the west coast of peninsular Malaysia, Ismail et al. (2002) found that goosegrass germination was inhibited by a water potential of −0.80 MPa.

TABLE 5. Model efficiency index (EF), mean bias error (MBE), and coefficient of the linear regression (*m*) between observed and simulated data (evaluation data set).

| Species | Soil type | Year | WeedTurf + SHAW[a] | | |
			EF	MBE	*m*
				%	
Large crabgrass	Loam	2001	0.98	3.2	0.93
	Loam	2002	0.95	4.6	1.01
Green foxtail	Loam	2001	0.94	4.9	0.93
	Loam	2002	0.91	8.1	0.96
Goosegrass	Loam	2001	0.81	−12.7	1.08
	Loam	2002	0.96	−5.0	0.98
Yellow foxtail	Loam	2001	0.96	1.5	0.90
	Loam	2002	0.96	−2.2	0.90

[a] Abbreviation: SHAW, Simultaneous Heat and Water.

These disparities are not surprising because seeds of the same species collected in locations with different climates, such as Italy, Malaysia, and the United States, may differ in their response to water stress, as occurred with accessions of green foxtail from different states in the United States in response to temperature (Forcella et al. 2000). We do not know at this time whether variability in laboratory-generated results of base temperatures and base water potentials are associated with variability of responses of seeds to these same factors in field settings. However, the results reported by Grundy et al. (2003) for common lambsquarters (*Chenopodium album* L.) emergence timing are encouraging; that is, seeds originating from disparate geographic locations responded similarly to soil microclimate. Possibly, various dormancy and maternal environment effects could be specific to locations and populations, but overwinter stratification, etc., may alleviate these influences and result in homogeneity of emergence timing responses among populations within a species.

Evaluation of the SHAW Model

The SHAW model simulation of soil temperature in 2001 in sandy-loam soil and in 2003 in both soil types was satisfactory with EF values ranging from 0.97 to 0.98 and MBE of 0.13 and 0.52 C for the sandy-loam soil in 2001 and 2003, respectively, and −0.12 C for the loam soil (Figure 2). Near-surface soil temperature (Figure 2) was underpredicted in sandy-loam soil throughout the emergence period (from March to July) in 2002, with an MBE of −1.60 C (EF = 0.87). The larger discrepancies between measured and predicted temperatures occurred when temperatures began to rise after mid-April.

Water content tended to be underpredicted in sandy-loam soil, with MBE values of −0.025 and −0.017 m^{-3} m^{-3} in 2002 and 2003, respectively. The EF values ranged from 0.65 to 0.71. The simulation of soil water content in loam had an EF value of 0.82 in 2002 with MBE of −0.008 m^3 m^{-3} and EF of 0.71 in 2003 with MBE of −0.022 m^3 m^{-3} (Figure 3). The errors associated with SHAW simulations were remarkably small considering the cross-continent separation between model development and application. EF was always closer to 1 than 0, and MBE always was < 10% of the range of observed values.

Modelling Emergence

WeedTurf Calibration

Base temperatures and base water potentials determined from growth chamber experiments (as described previously) were used in the WeedTurf model to predict emergence in the field. Table 3 shows all the parameters and input variables found by systematically varying T_o and K_t and repeating the calculation of *a* and *b* values of the Gompertz function until the best fit least squares regression was obtained. The resulting optimum temperatures (T_o) were 25 and 26 C. These values were essentially identical to those reported previously for these species (Baskin and Baskin 1998; Ismail et al. 2002; King and Oliver 1994; Swanton et al. 1999). Table 4 shows the EF, MBE, and regression coefficients for these calibration runs.

Use of SHAW Model Output for Simulating Emergence

Accuracy of simulated emergence from WeedTurf using measured soil temperature and water potential and from WeedTurf using soil parameters simulated by SHAW model is shown in Table 4. In both cases, emergence of large crabgrass was simulated by the model for all 3 yr on sandy-loam soil and loam soil in 2003 with EF values exceeding 0.96. In the sandy-loam soil in 2002, the WeedTurf prediction of the onset of large crabgrass emergence was better using measured soil temperature and water potential, but the complete germination time course in the subsequent period was predicted accurately using SHAW model output. Simulated green foxtail emergence also was satisfactory in both soil types and over all years. The lowest EF value of 0.87 was in 2001 using temperature and water potential from the SHAW model (Table 4).

The WeedTurf model predicted the time courses of goosegrass and yellow foxtail emergence in the calibration data sets less well. Goosegrass emergence predictions were reasonable when observed temperature and water potential data were used but underestimated and delayed by the model using SHAW model output, with MBE values of −10.8 and −4.0%, respectively (Table 4). In this case, the disparity between model predictions and real emergence data might be reduced by improving the prediction of soil temperature and water potential made by the SHAW model, especially across years.

Yellow foxtail emergence was overestimated when SHAW model output was used for 2001 in sandy-loam soil (MBE = 6.7%) and underestimated in 2002 and 2003 (MBE = −9.1 and −4.8%, respectively). Using observed soil temperature and soil water potential, the simulation improved in 2002 in sandy-loam soil and in 2003 in loam soil but not in 2001 and 2003 in sandy-loam soil (Table 4). Therefore, the SHAW model output is only one of the causes of WeedTurf's poor prediction of yellow foxtail emergence.

Independent Evaluation of WeedTurf

WeedTurf simulations of emergence in the 2001 and 2002 native loam soil (evaluation data set) resulted in EF values ranging from 0.81 to 0.98 (Table 5). Predicted emergence of large crabgrass, green and yellow foxtail resulted in an EF better than 0.91. Goosegrass emergence was underestimated, especially in 2001, where the lowest EF value
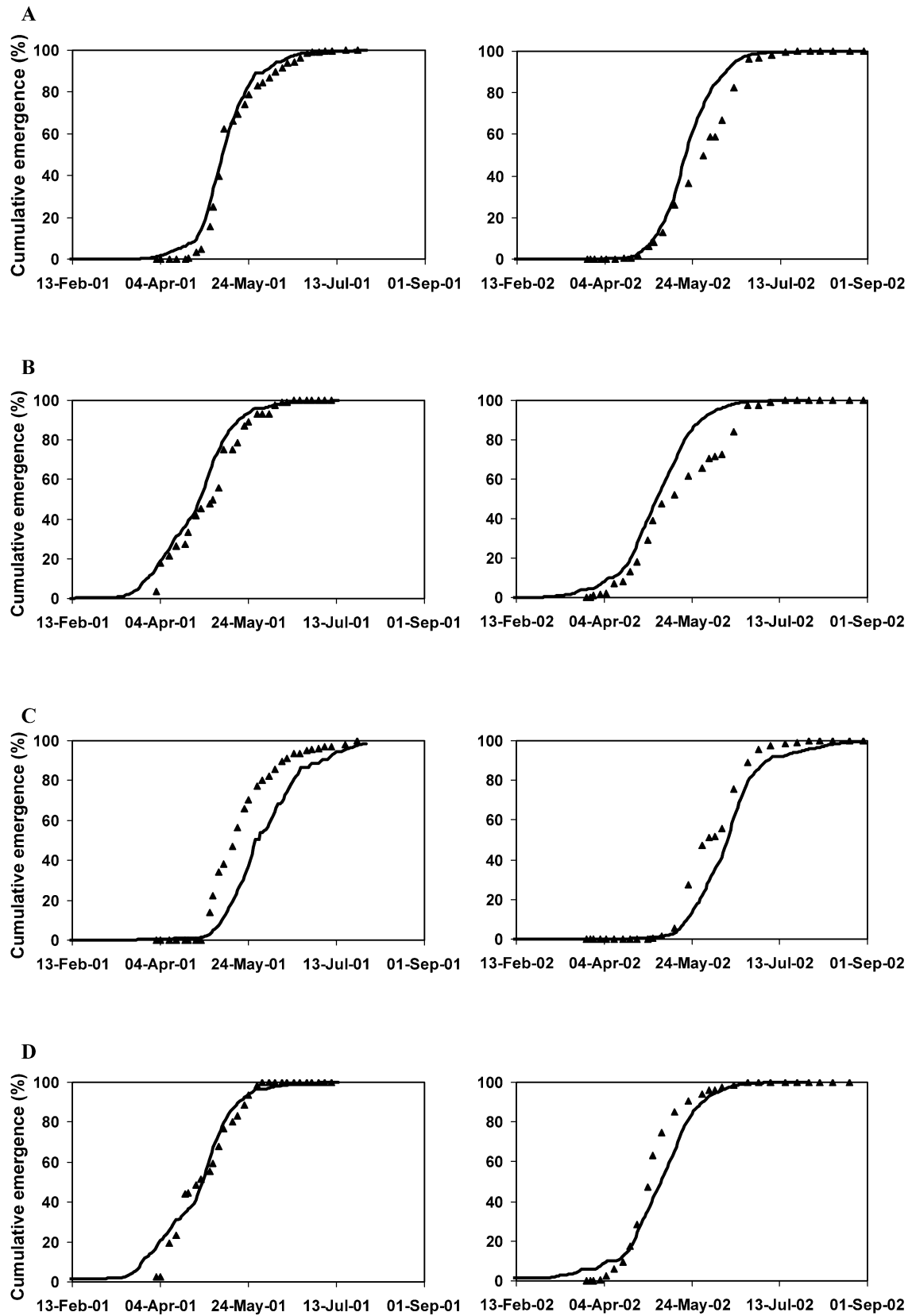
FIGURE 4. Large crabgrass (A), green foxtail (B), goosegrass (C), and yellow foxtail (D) seedling emergence at Legnaro in loam soil fitted using the WeedTurf model with Simultaneous Heat and Water (solid black line) and observed emergences (▲) (evaluation data set).
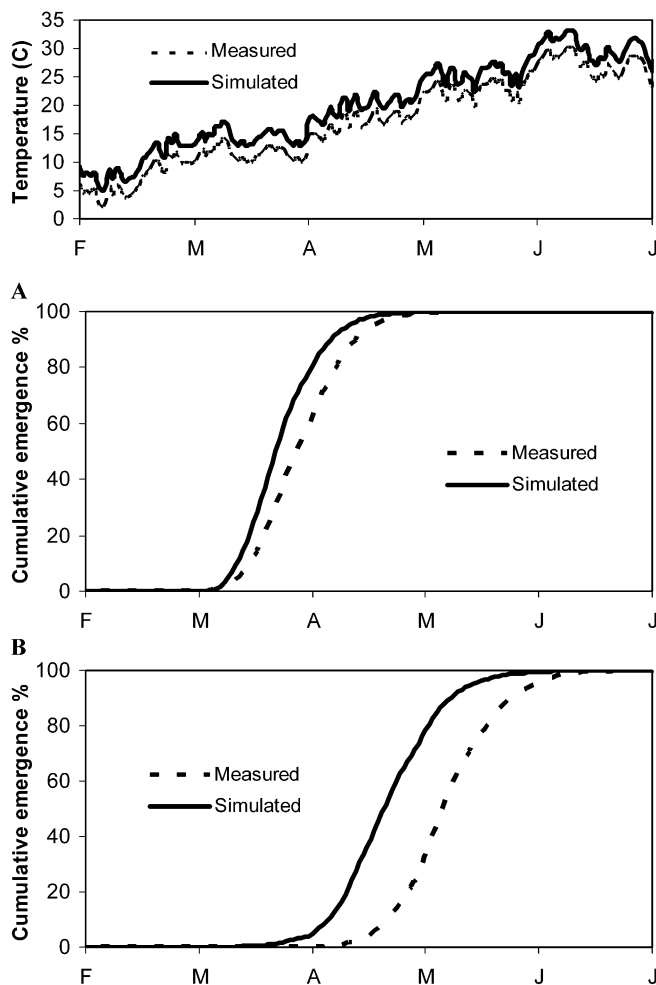
FIGURE 5. Effect of overestimating soil temperature on cumulative emergence of two hypothetical species with base temperature of 0 C (A) and 10 C (B). If the temperature is overestimated throughout the emergence period (in this example, the real soil temperature is 3 C lower than estimated soil temperature), then simulated cumulative emergence is greater than measured emergence in both species but markedly greater for the species with the higher base temperature. In this example, the Gompertz function was the same in both simulations, only T_b in the calculation of hydrothermal time was changed (no water stress was considered: $\Psi_i > \Psi_b$).

(0.81) and MBE (−12.7%) occurred (Figure 4C). The predicted emergence of yellow foxtail in loam soil showed high EF values in both years, even if the model was unable to describe emergence accurately during the initial period of the growing season (February to April) (Figure 4D). In 2002, the model overestimated the green foxtail emergence especially from May to June (MBE of 8.1%) and this disparity lowered the EF value to 0.91.

On the basis of these results, we concluded that the WeedTurf model can be used to predict large crabgrass and green foxtail emergence, whereas prediction of goosegrass and yellow foxtail emergence needs to be improved. Importantly, the SHAW model simulation errors showed more negative influence on predicting the emergence pattern of goosegrass than crabgrass and green foxtail. The cause of this different response may be the higher base temperature of goosegrass. If the soil temperature is over- or underpredicted, the simulated emergence is lower or greater than measured emergence and this difference is greater for the

species with the higher base temperature (an example is reported in Figure 5).

The case of yellow foxtail is different because calibration of the SHAW model will not necessarily improve predicted emergence. In particular, the emergence model was unable to accurately predict the onset of emergence, which is the critical period for implementing weed control practices, especially the use of preemergence herbicides in turf. Therefore, a clear need exists to review and refine the model for this species.

Further research will determine the utility of the WeedTurf model as a support for management decisions of weed control in turf. Similar types of software to predict weed emergence in arable fields are being used in various regions of the United States and Australia (Archer et al. 2002; Walsh et al. 2002), and the opinions of farmers and crop advisors on the programs are positive.

WeedTurf has demonstrated the ability to predict weed emergence with some accuracy. The current objective is to make these models accessible to turf managers and gardeners through interactive computer software (through the World Wide Web, as well as information by radio, television, and other media). Such software would help users determine the critical timing of weed removal and provide greatly enhanced recommendations for the application timing of preemergence and postemergence herbicides. Through improved and more effectively timed herbicide applications, rates, soil retention times, and probabilities of off-site transport can be reduced and environmental quality enhanced.

Sources of Materials

Acknowledgments

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